UGO AMALDI

50 Selected Scientific Papers
1964 - 2015

Experimental Nuclear Physics

1. ***Inner–shell proton binding energies in C^{12} and Al^{27} from the (e, e'p) reaction using 550 MeV electrons,*** U. Amaldi, G. Campos Vanuti, G. Cortellessa, G. Fronterotta, A. Reale, P. Salvadori, P. Hillman, Phys. Rev. Letters, **13**, 341–343, **1964**.

2. ***Proton angular distribution in the high energy ^{12}C (e, e'p)^{11}B reaction*** , U. Amaldi, G. Campos Vanuti, G. Cortellessa, E. De Sanctis, S. Frullani, R. Lombard, P. Salvadori, Phys. Letters, **25B**, 24–26, **1967**.

Notes: In 1963 U.A. presented to the Experimental Committee of the Frascati National Laboratories of INFN a new experiment of the type proposed few years before by Jacob and Maris, two Brazilian theorists. With the internal beam of the Frascati electronsynchrotron the ISS group led by Amaldi produced for the first time the nuclear reaction (*e,e'p*) in which an electron *e* expells from a nucleus a proton *p* detected *in coincidence* with the scattered electron *e*. The kinematics is such that the binding energy and the momentum of the proton can be measured simultaneously in this *quasi-free scattering*. The angular distribution reported in Paper 2 was judged by D.H. Wilkinson as "the most direct proof" of the validity of the nuclear shell model (Comments on Nuclear and Particle Physics, 2, 48, 1968). For this work U.A.received the Grimaldi Prize from the Italian Physical Society. Since then this new research line has been widely pursued, in particular at the Jefferson Laboratory (for a review paper see: D. Dutta et al, *Quasielastic (e,e'p) reaction on C^{12}, Fe^{56} and Au^{197}*, Phys. Rev. C68, 2003.)

Experimental Atomic Physics

3. ***Use of a two–channeltron coincidence in a new line of research in atomic physics,*** U. Amaldi, A. Egidi, R. Marconero, G. Pizzella, Rev. Sci. Instru., **40**, 1001 – 1004, **1969**

4. ***Value and limitations of quasi–free electron scattering experiments on atoms***, U. Amaldi and C. Ciofi degli Atti, Nuovo Cimento **66A**, 129–138, **1970**

Notes: Prompted by the results obtained in nuclei, U.A. decided to apply the same principle to the extraction of electrons from atoms. In spite of an enormous amount of information already obtained by scattering electron on atoms and molecules, nobody had ever made a *quasi-free scattering experiment* of the type *(e,2e)* in which the two electrons are detected in coincidence. A new experimental technique had to be invented and developed: the coincidence between two 'channeltrons', which can detect few keV electrons. For these developments U.A.was joined by Guido Pizzella and his University of Rome group, who were using spherical electrostatic analyzers,

followed by channeltrons, to measure the solar wind in space. Paper 3 describes the first experiment on carbon performed using a thin plastic film. It opened the way to a flourishing field of research that now is called "*electron momentum spectroscopy*". Two of Amaldi's graduate students (R. Camilloni and G. Stefani) worked with the apparatus for years and then built at Frascati a new one opening the way to studies on gas targets (R. Camilloni et al, Phys. Rev. Letters 29, 618, 1972). Stefani's thesis concerned the study of the (e,2e) reaction in solids, a research field which was developed at the beginning of the century

Thirty years later in the preface to the proceedings of the *Int. Conf. on Coincidence Spectroscopy* (Journal de Phys 9, 1999) it was written: "Coincidence Spectroscopy started in 1969 with the publication of seminal papers by Erhardt and by Amaldi".

Experimental Particle Physics: Strong Interactions

5. ***Proton-proton elastic scattering and nucleon resonance production at high energies*,** J. V. Allaby et al and U. Amaldi et al, Nucl. Phys b52, 316-382, **1973.**
6. ***Measurements of the proton–proton total cross–section by means of Coulomb scattering at the CERN Intersecting Storage Rings***, U. Amaldi, R. Biancastelli, C. Bosio, G. Matthiae and J.V. Allaby, W. Bartel, M.M. Block, G. Cocconi, A.N. Diddens, R.W. Dobinson, J. Litt, A.M. Wetherell, Phys. Letters, **43B**, 231–236, **1973.**
7. ***Diffraction of hadronic waves***, U. Amaldi, M. Jacob and G. Matthiae, Ann. Rev. Nucl. Sci., **26**, 385–456, **1976**.
8. ***The real part of the forward proton–proton scattering amplitude measured at the CERN Intersecting Storage Rings***, U. Amaldi, G. Cocconi, A.N. Diddens, R.W. Dobinson, J. Dorenbosch P. Duinker, D. Gustavson, J. Meyer, K. Potter, A.M. Wetherell, A. Baroncelli and C. Bosio, Phys. Letters 66B, 390–394, **1977.**
9. ***Impact parameter interpretation of proton–proton scattering from a critical review of all ISR data***, U. Amaldi and K.R. Schubert, Nucl. Phys., 301, **1980.**

In the years 1969- 1978 U.A. led the ISS group and Giuseppe Cocconi lead the CERN group of what became known as the Rome-CERN Collaboration. Paper 5 is the concluding one of a series of measurement performed at the CERN Proton Synchrotron.

At the Intersecting StorageRings (ISR) U.A. performed personally the analysis of the data on proton-proton elastic scattering, taken with a detector system invented to get detectors very close to the circulating beams. Since then these devices are called '*Roman Pots*' and regularly reproduced in all. At the end of 1972 he discovered the first indications of a fully unexpected phenomenon: the total proton-proton cross-section increases with energy [Paper 6]. With some delay the same phenomenon was observed by the CERN-Stony Brook Collaboration. Because of his contributions to the discovery, he presented the new results of both experiments in a CERN seminar, gave the general review talk at the 1973 International Conference of Aix–en–Provence (*Elastic scattering and low multiplicities*, U. Amaldi, Suppl. Journal Physique, 34, Cl, 241–259, 1973) and was invited to write an article for

Scientific American (*Proton interactions at high energies*, U. Amaldi, Scientific American, 299, 36–46, 1973).

The overall results obtained in high energy proton-proton collisions were summarized in Paper 7. The accurate measurement of the forward real part of Paper 8 confirmed the new picture which had emerged from the discovery of the rising cross-section and the analysis of Paper 9 agreed with the results U.A. first obtained in 1973 after the discovery of the rising cross-sections: this phenomenon is of *peripheral nature* and in the ISR energy range its phenomenology agrees with a simple geometrical model. This intuitive and much quoted paper (200 citations by the end of 2015) concluded ten years of activity in the field of strong interactions.

Experimental Particle Physics: Electroweak Interactions

10. ***Measurement of the circular polarization of the bremsstrahlung produced by electrons from Tl^{204},*** U. Amaldi, M. Bernardini, P. Brovetto and S. Ferroni, Nuovo Cimento 11, 415–423, **1959**.
11. ***Measurement of the polarization of positive muons produced in high energy antineutrino interactions,*** CHARM Coll., Zeitschrift für Physik C17, 211–217, **1983.**
12. ***New limits on the single–photon decay of orthopositronium***, U. Amaldi, G. Carboni, B. Jonson and J. Thun, Phys. Letters 153B, 444–448, **1985**.
13. ***A search for neutrino oscillations,*** CHARM Coll., Zeitschrift für Physik **C40,** 171–192, **1988**.
14. ***Experimental results on neutrino-electron scattering***, CHARM Collaboration, Eur. Phys. Journal C41, 567-589, **1989.**
15. ***Experimental study of the triple–gluon vertex,*** DELPHI Collaboration, Phys. Lett. 255B, 466, **1991**.
16. ***m_b at M_Z,*** DELPHI Collaboration, Phys. Letters B418, 430-442, **1998**.
17. ***Final results from DELPHI on the searches for SM and MSSM Neutral Higgs bosons***, DELPHI Collaboration, Eur. Phys. J., C 32, 145-187, **2004**.

Notes: Paper 10, which describes an experiment initiated shortly after the discovery of parity non conservation, was performed using a powerful magnet located in the basement of ISS. Having left weak interactions for fifteen years, at the beginning of the seventies, together with Klaus Winter and Guido Barbiellini, U.A. founded the Cern-Hamburg-Amsterdam-Rome-Moscow (CHARM) Collaboration to construct a 20 m long Carrara marble calorimeter and perform experiments in the CERN Super Proton Synchrotron (SPS) neutrino beam. CHARM published almost hundred papers.

The three quoted here (Papers 11, 13 and 14) are among those to which U.A. has given personal substantial contributions. Paper 11 describes the final results of a novel experimental idea proposed by U.A. in 1975: the measurement of the

polarization of the muons produced by neutrinos to check the properties of the charged weak current. The muons were produced by neutrinos in the upstream iron calorimeter of the CDHS Collaboration. G. Barbiellini was the prime mover of the very delicate experiment aiming at identifying neutrino-electron scattering events (Paper 13). This was made possible by the upgrading proposed and lead by U.A., which aimed at the improvement of the CHARM angular resolution by the introduction in the calorimeter of about 20'000 aluminium streamer tubes (Paper 24).

U.A. was also responsible for the construction of the 'close' detector needed to search for neutrino oscillations (Paper 14), a scientific problem which was barely possible to attack in the 80's and which will continue to occupy experimental physicists for many decades.

In 1980, with a small group of friends and colleagues U.A. founded the DELPHI collaboration and was its spokesman for fourteen years, when he decided to move to hadrontherapy. From the beginning his interests were focused on the search of the Higgs boson(s) and the properties and possible unification of the electroweak and strong forces. The Higgs search initiated with the design of the experiment and lasted twenty years involving hundreds of physicists. Paper 17, the concluding one, gives - in the framework of the Standard Model – the lower limit $m_H > 114.1$ GeV/c^2 at the 95% confidence level.

Papers 15 and 16 are two DELPHI firsts: the measurement of the strength of the triple gluon vertex, present only in gauge theories of the strong force, and the observation that the mass of the b-quark 'runs', i.e. varies with the energy scale.

Theory and phenomenology of the strong and the electroweak interactions

18. ***Nucleon–nucleon diffraction scattering,*** U. Amaldi, and F. Selleri, Phys. Rev. **128**, 2772–2783, **1962**.
19. ***Pion production amplitudes and nucleon–nucleon interaction,*** U. Amaldi, Review of Modern Physics **39**, 649–656, **1967**.
20. ***Comprehensive analysis of data pertaining to the weak neutral current and the intermediate vector boson masses***, U. Amaldi, A. Böhm, L.S. Durking, P. Langacker, A.K. Mann, W.J. Marciano, A. Sirlin and H.H. Williams, Phys. Rev., D36, 1385 – 1407, **1987**.
21. ***Comparison of grand unified theories with electroweak and strong coupling constants measured at LEP***, U. Amaldi, W. de Boer and H. Fürstenau, Phys. Letters **260B**, 447 – 455, **1991**.

Notes: Papers 18 and 19 are the first and the last of a series of five papers, two with F. Selleri and two with Biancastelli and Francaviglia, who graduated with U.A. on these subjects. Paper 18 contains the *first* explicit use of the unitarity relation to compute, from a model of the inelastic channels based on the exchange of a pion, the energy dependence of the imaginary parts of the five elastic amplitudes that describe proton-proton scattering. The Livermore Group used the imaginary parts of the nucleon-nucleon phase-shifts of Paper 19 as input in the final phase-shift analysis extended to more than 1 GeV (M.H. MacGregor, R.A. Arndt and R.M. Wright, Phys.Rev. 169, 1149, 1968).

Paper 20 is the result of a long lasting effort, coordinated by Paul Langacker, to combine all the existing data on the weak neutral current. By the end of 2004 the paper had about 900 citations. U.A., together with H.H. Willimas, brought his competences in the field of neutrino physics. This paper contained an attempt to extrapolate the measured electromagnetic, weak and strong constants to very high energy to check the consistency of the data with the prediction of supersymmetric Grand Unified Theories (GUT). In 1991 the approach was applied in Paper 21 by using the much more precise recent LEP data with the conclusion that the simplest Grand Unified Minimal Supersymmetric Standard Model was consistent with the data. The novelty of the statistical approach and the relevance of the results were widely discussed not only in physics papers and conferences, but also in general physics journals (New Scientist, Physics World, Nature, Science...) and even in daily newspapers (The Guardian, Corriere della Sera, Journal de Genève,...). Paper 21 prompted many new developments and by 2026 it had been cited more than 2600 times. As far as the number of citations is concerned, it is the eighth among the more than 35'000 papers published by CERN scientists. Moreover it is on the list of the about 150 papers that have been cited more than 1000 times in the all history of particle physics.

Particle Detectors

22. A detector for neutral–current interactions of high energy neutrinos, CHARM Coll., NIM 178, 27, **1980**.

23. Fluctuations in calorimetry measurements, U. Amaldi, Physica Scripta 23, 409–424, **1981**.

24. The limited streamer tube system of the CHARM Collaboration, M. Jonker, F. Udo, U. Amaldi et al, NIM 215, 361–368, **1983**.

25. Physics and detectors at the Large Hadron Collider (LHC) and the CERN linear collider (CLIC), in *Proceedings of the Workshop on physics and future accelerators*, La Thuile and Geneva, 7–13 Jan. 1987**,** J.H. Mulvey (Ed.), Vol. I, 323–352, **1987**.

26. An experimentalist's overview of the parallel development of accelerators and detectors, U. Amaldi, in *Instrumentation in elementary particle physics*, C.W. Fabjan and J.E. Pilcher (Eds.), World Scientific, Singapore, 284–297, **1988.**

27. The DELPHI detector at LEP, Delphi Collaboration., NIM A 303, 233, **1991.**

28. Advanced Quality Assurance for CNAO, U. Amaldi, W. Hadjas, S. Iliescu,. Malakhov, J. Samarati, F. Sauli and D. Watts, NIM A, 617, 248, **2010.**

29. Construction, test and operation of a proton range radiography system, U. Amaldi, A. Bianchi, Y.-H. Chang, A. Go, W. Hadjas, N. Malakhov and J. Samarati, NIM A, 629, 337, **2011.**

30. Fast readout of GEM detectors for medical imaging, M. Bucciantonio, U. Amaldi, R. Kieffer, N. Malakhov, F. Sauli and D. Watts, NIM A 718, 160, **2012**.

Notes: U.A. devoted a lot of work to the design, development and construction of sophisticated detectors. Papers 22, 24 and 27 describe the two largest instruments he contributed to design and realize: the CHARM marble calorimeter and the 3000 tons DELPHI detector for LEP. Paper 23, the result of many years of activity in the detection of electromagnetica and hadronic showers, was selected for publication in *Experimental techniques in high–energy physics*, T. Ferbel (Ed.), Addison–Wesley, Amsterdam, 325–370, 1987. It has reached 300 citations.

Having participated for about thirty years in the increasing sophistication and dimensions of both particle detectors and accelerators, in 1988 U.A. published Paper 26, where his view of these parallel and intertwined developments is presented.

The detector built and tested for proton radiography is described in papers 29 and 30.

Accelerators for High-energy Physics

31. ***Ottica di iniezione,*** G. Cortellessa, U. Amaldi and A. Reale, in *L'elettrosincrotrone e i Laboratori di Frascati*, G. Salvini (Ed.), Suppl. Nuovo Cimento 24, 298-311, **1962**.

32. ***A possible scheme to obtain e^-e^- and e^+e^- collisions at energies of hundreds of GeV***, U. Amaldi, Phys. Letters 61B, 313–316, **1975.**

33. ***Linear colliders with superconducting cavities,*** U. Amaldi, H. Lengeler and H. Piel, CERN EF/76–8 and CLIC Note 1986-15, **1976**.

34. ***Colliding linacs***, in *Proceedings of the International Symposium on Lepton and Photon Interactions of High Energies*, Batavia, August 1979, T.B.W. Kirk and M.D.I. Abarbanel (Ed.s), FNAL, Batavia, 314–326, **1979**.

35. ***Introduction to the next generation of linear colliders,*** U. Amaldi, in *Frontier of Particle Beams*, M. Month and S. Turner (Ed.s), Springer Verlag, Berlin-Heidelberg-New York-London-Paris-Tokyo , 341–392, **1987**.

36. ***Report of the advisory panel on the prospects for e^+e^-colliders in the TeV range,*** K. Johnsen (chairman), U. Amaldi, J.D. Lawson, B.W. Montague, W. Schnell, S. Van Der Meer and W. Willis, CERN Yellow Report, CERN 87–12, **1987**.

37. ***TeV electron–positron collisions with luminosities of 10^{34} $cm^{-2}s^{-1}$ using the CERN tunnels for the damping rings,*** U. Amaldi, Nucl. Instrum. Methods A243, 312–322, **1986.**

Notes: During his graduate and postgraduate studies, Enrico Persico - who was an exceptional teacher and friend of Enrico Fermi - introduced U.A. to particle accelarators. The he had the chance to join the Italian effort, directed by Giorgio Salvini, to build the Frascati 1 GeV electrosynchrotron with responsibility for the focussing of the injector beam. For this he designed and built the first Italian quadrupole (Paper 31) that has been in use for thirty years.

In 1975, to bypass the limitations of the extrapolation of e^+ e^- storage rings to higher energies, he proposed the use of two opposite superconducting linacs to

obtain energies larger than 300 GeV in the centre-of-mass, with a collider having no radiation problem and thus with a cost proportional to the energy (Paper 32). This is the *first published paper* on linear colliders of energies above few hundreds GeV. This kind of accelerator was proposed as possible basis for a world-wide enterprise, at the "*International Study Group on Future Accelerators and High Energy Physics*" held at Serpukhov in May 1976. The proposal, which contained also 'damping rings', was discussed in physics laboratories worldwide, and in less than one year the idea of linear colliders was common place and cost estimates were made (Paper 33). At the same time it was realized that similar suggestions had been independently made 10 years before by Maury Tigner to obtain low energy electron–electron collisions (few GeV) but too easily forgotten. At Novosibirsk Budker et al had been discussing similar ideas without publishing them, so that they were not known in the West. The history of this development is summarized in the invited talk U.A. gave at the 1979 Batavia Lepton-Photon Conference (Paper 34), the *first* review paper on linear colliders ever given at a physics Conference. In 2004 the international community decided that the next world accelerator after LHC will be an electron-positron superconducting linear collider.

Paper 35 reviews the theory of linear colliders. In 1985-1987 he participated in the work of the *CERN LInear Collider* (CLIC) *Advisory Panel* under the chairmanship of K. Johnsen (Paper 36), which was an essential basis for the deliberation of the Committee chaired by C. Rubbia on the future of CERN. A workshop was held in La Thuile to compare the physics potentialities of CLIC and LHC and discuss the future CERN program; U.A. gave the summary talk (Paper 25). Another contribution concerned the use of the LEP tunnel to locate the very long damping rings needed for a high-luminosity collider (Paper 37).

Hadrontherapy

38. ***Per un centro di teleterapia con adroni***, U. Amaldi and G. Tosi, CERN/PPE, **1991**.

39. ***Design of a centre for biologically optimised light ion therapy in Stockholm***, A. Brahme, R. Lewensohn, U. Ringborg, U. Amaldi, F. Gerardi, S. Rossi , NIM B184, 569-588, **2001**.

40. ***LIBO—a linac-booster for protontherapy: construction and tests of a prototype***, U. Amaldi; P. Berra, K. Crandall, D. Toet, M. Weiss, R. Zennaro, E. Rosso, B. Szeless, M. Vretenar, C. Cicardi, C. De Martinis, D. Giove, D. Davino, M. Masullo and V. Vaccaro, NIM A 521, 512-529, **2004.**

41. ***Radiotherapy with beams of carbon ions***, U. Amaldi and G. Kraft, Reports Progr. Phys. 6, 1861, **2005**.

42. ***CLUSTER: concept study and design of a low-medium beta accelerating structure,*** U. Amaldi, A. Citterio, M. Crescenti and R. Zennaro, Nucl. Phys. B 172, 277, **2007**.

43. ***High Frequency Linacs for Hadrontherapy,*** U. Amaldi, S.Braccini, P. Puggioni, Reviews of Accelerator Science and Technology, World Scientific Publishing, Vol. 2, 111-131, **2009**.

44. ***Accelerators for Hadrontherapy: From Lawrence Cyclotrons to Linacs***, U. Amaldi, R. Bonomi, S. Braccini, M. Crescenti, A. Degiovanni, M. Garlasché, A. Garonna, G. Magrin, C. Mellace, P. Pearce, G. Pittà, P. Puggioni, E. Rosso, S. Verdú-Andrés, R. Wegner, M. Weiss and R. Zennaro, NIM A, 620, 563-577, **2010**.

45. ***Cyclinac Medical Accelerators Using Pulsed C6+/H2+ Ion Sources*****,** A. Garonna, U. Amaldi, R. Bonomi, D. Campo, A. Degiovanni, M. Garlasché, I. Mondino, V. Rizzoglio, S. Verdú-Andrés, EBIST2010 Proceedings, Journal of Instrumentation, 5 C09004, IoP Publishing for SISSA, 1-17, **2010**.

46. ***TERA High Gradient Test Program of RF Cavities for Medical Linear Accelerators*****,** A. Degiovanni, U. Amaldi, R. Bonomi, M. Garlasché, A. Garonna, S. Verdú Andrés, R. Wegner, NIM A, Volume 657, Issue 1, 55-58, **2011**.

47. ***Acceleration tests of a 3 GHz proton linear accelerator (LIBO) for hadrontherapy,*** C. De Martinis, D. Giove, U. Amaldi, P. Berra, K. Crandall, M. Mauri, M. Weiss, R. Zennaro, E. Rosso, B. Szeless, M. Vretenar, M.R. Masullo, V. Vaccaro, L. Calabretta, A. Rovelli NIM A, Vol. 681, 10-15, **2012**.

48. ***CABOTO, a high-gradient linac for hadrontherapy,*** S. Verdu Andrés, U. Amaldi, A. Faus-Golfe, Journal of Radiation Research 54(suppl 1) 55-61, **2013**.

49. ***Proton and carbon linacs for hadrontherapy***, U. Amaldi and A. Degiovanni, Proceedings of LINAC2014, 1207-1212, **2014**.

50. ***History of Hadrontherapy,*** U. Amaldi, Mod. Physics Letters A 30(17): 1540018, **2015**.

Notes: Paper 38 is the Note with which, in collaboration with G. Tosi of the European Institute of Oncology, U.A. proposed the realization of an Italian centre for hadrontherapy of deep-seated trumours with light ions.

Many volumes edited by U.A. in the years 1995-1997 (see 'Book as Ed.') describe the technical choices made by the TERA Foundation, created in 1992 and chaired since then by U.A., in the design of the 90 million Euro CNAO (Centro Nazionale di Adroterapia Oncologica), which is in construction in Pavia since 2002. Patients will be treated starting in fall 2008. The application of the same concepts and technical choices to the Karolinska centre in Stockholm is the subject of Paper 39.. Paper 42 describes a novel high efficiency accelerator for low energy hadrons and Paper 43 is a detailed presentation aof the linac technology for accelerating medical beams with applications to both protons and carbon ions.

In 1993 U.A. proposed to use protons linacs to treat patients and, in particular, he introduced a new type of accelerator, later called "cyclinac", formed of a cyclotron – used at around 30 MeV for the production of medical radioisotopes – and a linear accelerator (a 'linac') which runs at high frequency (3 GHz) and, having a large accelerating field, brings in about 15 metres one of the proton beams extracted from the cyclotron to the 200 MeV needed for the therapy of deep-seated tumours. Proton linacs for hadrontherapy have been the focus of TERA activities for many years, also in collaboration with research groups from CERN and INFN, brought to the construction and test of a prototype of a Side Coupled Linac, called LIBO for LInac BOoster (Papers 40 and 47). The first acceleration of protons with a high-frequency

linac described in these articles opened the way to the application of the same cyclinac concept to the acceleration of carbon ions (Papers 46 and 48).

Papers 41, 44 and 50 review the (1) the rationale and the status of the use of carbon ions in the treatment of radioresistant tumors (this paper was written with Gerhard Kraft, the promoter of the GSI 'pilot plan' and of the Heidelberg HIT project), (2) the history of the accelerators used in hadrontherapy, (3) the history of hadrontherapy till our days.